LANDFILLING

This chapter presents an overview of landfilling as a waste management strategy in relation to the development of material-specific emission factors for EPA's Waste Reduction Model (WARM). Estimates of the net greenhouse gas (GHG) emissions from landfilling most of the materials considered in WARM and several categories of mixed waste streams (e.g., mixed paper, mixed recyclables and mixed municipal solid waste (MSW)) are included in the chapter.

1. A SUMMARY OF THE GHG IMPLICATIONS OF LANDFILLING

When food scraps, yard trimmings, paper and wood are landfilled, anaerobic bacteria degrade the materials, producing methane (CH_4) and carbon dioxide (CO_2). CH_4 is counted as an anthropogenic GHG because, even if it is derived from sustainably harvested biogenic sources, degradation would not result in CH_4 emissions if not for deposition in landfills. The CO_2 is not counted as a GHG because is it considered part of the natural carbon cycle of growth and decomposition; for more information, see the text box on biogenic carbon in the Introduction & Background chapter. The other materials in WARM either do not contain carbon or do not biodegrade measurably in anaerobic conditions, and therefore do not generate any CH_4.

In addition to carbon emissions, some of the carbon in these materials (i.e., food scraps, yard trimmings, paper and wood) is stored in the landfill because these materials are not completely decomposed by anaerobic bacteria. Because this carbon storage would not normally occur under natural conditions (virtually all of the biodegradable material would degrade to CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastics and rubber that remains in the landfill is not counted as stored carbon because it is of fossil origin. Fossil carbon (e.g., petroleum, coal) is already considered "stored" in its natural state; converting it to plastic or rubber and putting it in a landfill only moves the carbon from one storage site to another.

EPA developed separate estimates of emissions from (1) landfills without gas recovery systems, (2) those that flare CH_4, (3) those that combust CH_4 for energy recovery, and (4) the national average mix of these three categories. The national average emission estimate accounts for the extent to which CH_4 will be flared at some landfills and combusted onsite for energy recovery at others.[1] The assumed mix of the three landfill categories that make up the national average for all material types are presented in Exhibit 1. These estimates are based on the amount of CH_4 recovered by U.S. landfills, as cited in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2009* (EPA 2011). WARM assumes that construction and demolition landfills do not flare or collect CH_4.

Exhibit 1: Percentage of CH_4 Generated from Each Type of Landfill

Material/Product	Percentage of CH_4 from Landfills without LFG Recovery	Percentage of CH_4 from Landfills with LFG Recovery and Flaring	CH_4 from Landfills with LFG Recovery and Electricity Generation (%)
Construction and Demolition Materials	100%	–	–
All Other Materials	28%	38%	34%

– = Zero Emissions.

[1] Although gas from some landfills is piped to an offsite power plant and combusted there, for the purposes of WARM, the simplifying assumption was that all gas for energy recovery was combusted onsite. This assumption was made due to the lack of information about the frequency of offsite power generation, piping distances and losses from pipelines.

2. CALCULATING THE GHG IMPACTS OF LANDFILLING

The landfilling emission factors are made up of the following components:

1. CH_4 emissions from anaerobic decomposition of biogenic carbon compounds;
2. Transportation CO_2 emissions from landfilling equipment;
3. Biogenic carbon stored in the landfill; and
4. CO_2 emissions avoided through landfill gas-to-energy projects.

As mentioned above, WARM does not calculate CH_4 emissions, stored carbon or CO_2 avoided for materials containing only fossil carbon (e.g., plastics, rubber). These materials have net landfilling emissions that are very low because they include only the transportation-related emissions from landfilling equipment. Some materials (e.g., newspaper and phone books) result in net storage (i.e., carbon storage exceeds CH_4 plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present, while others (e.g., food scraps) result in net emissions regardless of landfill gas collection and recovery practices. Whether the remaining materials result in net storage or net emissions depends on the landfill gas recovery scenario.

2.1 CARBON STOCKS AND FLOWS IN LANDFILLS

Exhibit 2 shows the carbon flows within a landfill system. Carbon entering the landfill can have one of several fates: exit as CH_4, exit as CO_2, exit as volatile organic compounds (VOCs), exit dissolved in leachate, or remain stored in the landfill.[2]

After entering landfills, a portion of the biodegradable material decomposes and eventually is transformed into landfill gas and/or leachate. Aerobic bacteria initially decompose the waste until the available oxygen is consumed. This stage usually lasts less than a week and is followed by the anaerobic acid state, in which carboxylic acids accumulate, the pH decreases, and some cellulose and hemicellulose decomposition occurs. Finally, during the methanogenic state, bacteria further decompose the biodegradable material into CH_4 and CO_2.

The rate of decomposition in landfills is affected by a number of factors, including: (1) waste composition; (2) factors influencing microbial growth (moisture, available nutrients, pH, temperature); and (3) whether the operation of the landfill retards or enhances waste decomposition. Most studies have shown that the amount of moisture in the waste, which can vary widely within a single landfill, is a critical factor in the rate of decomposition (Barlaz et al., 1990).

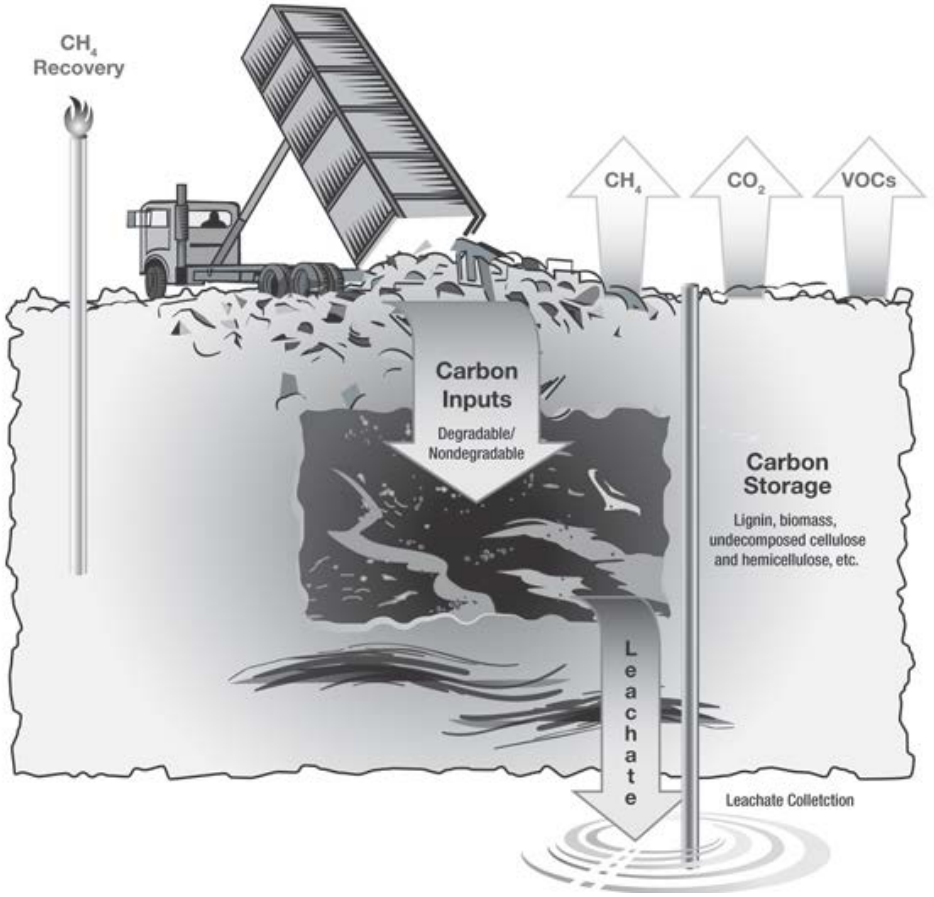
Among the research conducted on the various components of the landfill carbon system, by far the most to date has focused on the transformation of landfill carbon into CH_4. This interest has been spurred by a number of factors, including EPA's 1996 rule requiring large landfills to control landfill gas emissions (40 Code of Federal Regulations Part 60, Subparts Cc and WWW), the importance of CH_4 emissions in GHG inventories, and the market for CH_4 as an energy source. CH_4 production occurs in the methanogenic stage of decomposition, as methanogenic bacteria break down the fermentation products from earlier decomposition processes. Since CH_4 emissions result from waste decomposition, the quantity and duration of the emissions is dependent on the same factors that influence waste degradability (e.g., waste composition, moisture). The CH_4 portion of each material type's emission factor is discussed further in section 2.2.

Carbon dioxide is produced in the initial aerobic stage and in the anaerobic acid stage of decomposition. However, relatively little research has been conducted to quantify CO_2 emissions during these stages. Emissions during the aerobic stage are generally assumed to be a small proportion of total

[2] The exhibit and much of the ensuing discussion are taken directly from Freed et al. (2004).

organic carbon inputs, and a screening-level analysis indicates that less than 1 percent of carbon is likely to be emitted through this pathway (Freed et al., 2004). Once the methanogenic stage of decomposition begins, landfill gas *as generated* is composed of approximately 50 percent CH_4 and 50 percent CO_2 (Bingemer and Crutzen, 1987). However, landfill gas *as collected* generally has a higher CH_4 concentration than CO_2 concentration (sometimes as much as a 60 percent: 40 percent ratio), because some of the CO_2 is dissolved in the leachate as part of the carbonate system ($CO_2 \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- \leftrightarrow CO_3^{2-}$).

Exhibit 2: Landfill Carbon Mass Balance



Source: Freed et al. (2004).

To date, very little research has been conducted on the role of VOC emissions in the landfill carbon mass balance. Given the thousands of compounds entering the landfill environment, tracking the biochemistry by which these compounds ultimately are converted to VOC is a complex undertaking. Existing research indicates that ethane, limonene, *n*-decane, *p*-dichlorobenzene and toluene may be among the most abundant landfill VOCs (Eklund et al., 1998). Hartog (2003) reported non-CH_4 volatile organic compound concentrations in landfill gas at a bioreactor site in Iowa, averaging 1,700 parts per million (ppm) carbon by volume in 2001 and 925 ppm carbon by volume in 2002. If the VOC concentrations in landfill gas are generally of the order of magnitude of 1,000 ppm, VOCs would have a small role in the overall carbon balance, as concentrations of CH_4 and CO_2 will both be hundreds of times larger.

Leachate is produced as water percolates through landfills. Factors affecting leachate formation include the quantity of water entering the landfill, waste composition, and the degree of decomposition.

Because it may contain materials capable of contaminating groundwater, leachate (and the carbon it contains) is typically collected and treated before being released to the environment, where it eventually degrades into CO_2. However, leachate is increasingly being recycled into the landfill as a means of inexpensive disposal and to promote decomposition, increasing the mass of biodegradable materials collected by the system and consequently enhancing aqueous degradation (Chan et al., 2002; Warith et al., 1999). Although a significant body of literature exists on landfill leachate formation, little research is available on the carbon implications of this process. Based on a screening analysis, Freed et al. (2004) found that loss as leachate may occur for less than 1 percent of total carbon inputs to landfills.

In mass balance terms, carbon storage can be characterized as the carbon that remains after accounting for the carbon exiting the system as landfill gas or dissolved in leachate. On a dry weight basis, municipal refuse contains 30–50 percent cellulose, 7–12 percent hemicellulose and 15–28 percent lignin (Hilger and Barlaz, 2001). Although the degradation of cellulose and hemicellulose in landfills is well documented, lignin does not degrade to a significant extent under anaerobic conditions (Colberg, 1988). Landfills in effect store some of carbon from the cellulose and hemicellulose and all of the carbon from the lignin that is buried initially. The amount of storage will vary with environmental conditions in the landfill; pH and moisture content have been identified as the two most important variables controlling decomposition (Barlaz et al, 1990). These variables and their effects on each material type's emission factor are discussed further below.

2.2 ESTIMATING EMISSIONS FROM LANDFILLS

As discussed in section 2.1, when biodegradable materials such as wood products, food wastes and yard trimmings are placed into a landfill, a fraction of the carbon within these materials degrades into CH_4 emissions. The quantity and timing of CH_4 emissions released from the landfill depends upon three factors: (1) how much of the original material decays into CH_4, (2) how readily the material decays under different landfill moisture conditions, and (3) landfill gas collection practices. This section describes how these three factors are addressed in WARM.

2.2.1 Methane Generation and Landfill Carbon Storage

The first step is to determine the amount of carbon contained in degradable materials that is emitted from the landfill as CH_4, and the amount that remains in long-term storage within the landfill. Although a large body of research exists on CH_4 generation from mixed solid wastes, only a few investigators—most notably Dr. Morton Barlaz and co-workers at North Carolina State University—have measured the behavior of specific waste wood, paper, food waste and yard trimming components. The results of their experiments yield data on the inputs—specifically the initial carbon contents, CH_4 generation and carbon stored—that are required for calculating material-specific emission factors for WARM.

Barlaz (1998) developed a series of laboratory experiments designed to measure biodegradation of these materials in a simulated landfill environment, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). Each waste component (e.g., grass, branches, leaves, paper) was dried; analyzed for cellulose, hemicellulose and lignin content; weighed; placed in two-liter plastic containers (i.e., reactors); and allowed to decompose anaerobically under moist conditions (Eleazer et al., 1997). At the end of the experiment, the contents of the reactors were dried, weighed and analyzed for cellulose, hemicellulose, lignin and (in the case of food scraps only) protein content. The carbon in these residual components is assumed to represent carbon that would remain undegraded over the long term in landfills: that is, it would be stored.

Based on these components, Dr. Barlaz estimated the initial biogenic carbon content of each waste material as a percent of dry matter. Exhibit 3 shows the initial carbon contents of the wastes analyzed in Barlaz (1998).

Exhibit 3: Initial Biogenic Carbon Content of Materials Tested in Barlaz (1998)

Material	Initial Biogenic Carbon Content, % of Dry Matter
Corrugated Containers	47%
Newspaper	49%
Office Paper	40%
Coated Paper	34%
Food Scraps	51%
Grass	45%
Leaves	46%
Branches	49%
Mixed MSW	42%
Gypsum Board	5%

The principal stocks and flows in the landfill carbon balance are:

- Initial carbon content (Initial C);
- Carbon output as CH_4 (CH_4^C);
- Carbon output as CO_2 (CO_2^C); and
- Residual carbon (i.e., landfill carbon storage, LF^C).

The initial carbon content, along with the other results from the Barlaz experiments, are used to estimate each material type's emission factor in WARM. The Barlaz experiments did not capture CO_2 emissions in the carbon balance; however, in a simple system where the only carbon fates are CH_4, CO_2 and carbon storage, the carbon balance can be described as

$$CH_4^C + CO_2^C + LF^C = \text{Initial C}$$

If the only decomposition is anaerobic, then $CH_4^C = CO_2^C$.[3] Thus, the carbon balance can be expressed as

$$= \text{Initial C2} \times CH_4^C + LF^C = \text{Initial C}$$

Exhibit 4 shows the measured experimental values, in terms of the percentage of initial carbon for each of the materials analyzed, the implied landfill gas yield, and the sum of outputs as a percentage of initial carbon (Barlaz, 1998). As the sum of the outputs shows, the balance between carbon outputs and carbon inputs generally was not perfect. This imbalance is attributable to measurement uncertainty in the analytic techniques.

[3] The emissions ratio of CH_4 to CO_2 is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins, the ratio is 1.65 CH_4 per 1.55 CO_2; for protein, it is $C_{3.2}H_5ON_{0.86}$ (Barlaz et al., 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

Exhibit 4: Experimental Values for CH_4 Yield and Carbon Storage[a]

(a) Material	(b) Measured CH_4 Yield as a % of Initial Carbon	(c) Implied Yield of Landfill Gas (CH_4+CO_2) as a Proportion of Initial Carbon (c = 2 × b)	(d) Measured Proportion of Initial Carbon Stored	(e) Output as % of Initial Carbon (e = c + d)
Corrugated Containers	16%	32%	55%	88%
Newspaper	8%	15%	85%	100%
Office Paper	27%	54%	12%	66%
Coated Paper	12%	25%	79%	103%
Food Scraps	30%	59%	16%	75%
Grass	16%	32%	53%	86%
Leaves	6%	12%	85%	97%
Branches	6%	13%	77%	90%
Mixed MSW	11%	22%	19%	40%
Gypsum Board	16%	32%	64%	96%

[a] The CH_4, CO_2, and carbon stored from these experiments represents only the biogenic carbon in each material type.

To calculate the WARM emission factors, adjustments were made to the measured values so that exactly 100 percent of the initial carbon would be accounted for. After consultation with Dr. Barlaz, the following approach was adopted to account for exactly 100 percent of the initial carbon:

- For all materials except for coated paper, where the total carbon output is less than the total carbon input (e.g., corrugated containers, office paper, food scraps, grass, leaves, branches, mixed MSW, gypsum board), the "missing" carbon was assumed to be emitted as equal quantities of CH_4^C and CO_2^C. In these cases (corrugated containers, office paper, food scraps, grass, leaves, branches, mixed MSW and gypsum board), the CH_4^C was increased with respect to the measured values as follows:

$$\frac{\text{Initial C-LF}^C}{2} = CH_4^C$$

This calculation assumes that $CO_2^C = CH_4^C$. In essence, the adjustment approach was to increase landfill gas production, as suggested by Dr. Barlaz.

- For coated paper, where carbon outputs were greater than initial carbon, the measurements of initial carbon content and CH_4 mass were assumed to be accurate. Here, the adjustment approach was to decrease carbon storage. Thus, landfill carbon storage was calculated as the residual of initial carbon content minus ($2 \times CH_4^C$).

The resulting adjusted CH_4 yields and carbon storage are presented in Exhibit 5.

Exhibit 5: Adjusted CH_4 Yield and Carbon Storage by Material Type

Material	Adjusted[a] Yield of CH_4 as Proportion of Initial Carbon	Adjusted Carbon Storage as Proportion of Initial Carbon
Corrugated Containers	22%	55%
Newspaper	8%	85%
Office Paper	44%	12%
Coated Paper[b]	12%	75%
Food Scraps	42%	16%

Grass	23%	53%
Leaves	8%	85%
Branches	12%	77%
Mixed MSW	41%	19%
Gypsum Board	18%	64%

[a] CH_4 yield is adjusted in this table to account for measurement uncertainty in the analytic techniques to measure these quantities. For all materials other than coated paper, the yield of CH_4 was increased such that the proportion of initial carbon emitted as landfill gas (i.e., $2 \times CH_4$) plus the proportion that remains stored in the landfill is equal to 100% of the initial carbon.
[b] For coated paper, the proportion of initial carbon that is stored in the landfill is decreased such that the proportion of initial carbon emitted as landfill gas (i.e., $2 \times CH_4$) plus the proportion that remains stored in the landfill is equal to 100% of the initial carbon.

Dr. Barlaz's experiment did not test all of the biodegradable material types in WARM. EPA identified proxies for the remaining material types for which there were no experimental data. Magazines and third-class mail placed in a landfill were assumed to have characteristics similar to those observed for coated paper. Similarly, phone books and textbooks were assumed to behave in the same way as newspaper and office paper, respectively. Experimental results for branches were used as a proxy for dimensional lumber and medium-density fiberboard. Results for branches were also used as a proxy for wood flooring, except the ratio of dry-to-wet weight was adjusted to more accurately represent the moisture content of wood lumber (Staley and Barlaz, 2009). Drywall was assumed to have characteristics similar to gypsum board. Exhibit 6 shows the landfill CH_4 emission factors and the final carbon storage factors for all applicable material types.

Exhibit 6: CH_4 Yield for Solid Waste Components

Material/Product	Initial Biogenic Carbon Content	Adjusted Yield of CH_4 as Proportion Of Initial Carbon	Final (Adjusted) CH_4 Generation, $MTCO_2E$/Dry Metric Ton[a]	Final (Adjusted) CH_4 Generation ($MTCO_2E$ /Wet Short Ton)[b]
Corrugated Containers	47%	22%	2.93	2.52
Magazines/Third-Class Mail	34%	12%	1.18	1.02
Newspaper	49%	8%	1.04	0.90
Office Paper	40%	44%	4.94	4.26
Phone Books	49%	8%	1.04	0.90
Textbooks	40%	44%	4.94	4.26
Dimensional Lumber	49%	12%	1.60	1.30
Medium-Density Fiberboard	49%	12%	1.60	1.30
Food Scraps	51%	42%	5.99	1.63
Yard Trimmings				
Grass	45%	23%	2.92	0.80
Leaves	46%	8%	0.98	0.62
Branches	49%	12%	1.60	1.30
Mixed MSW	42%	41%	4.79	3.64
Drywall	5%	18%	0.24	0.20
Wood Flooring	49%	12%	1.60	1.09

[a] Final adjusted CH_4 generation per dry metric ton is the product of the initial carbon content and the final percent carbon emitted as CH_4 multiplied by the molecular ratio of carbon to CH_4 (12/16).
[b] CH_4 generation is converted from per dry metric ton to per wet short ton by multiplying the CH_4 generation on a dry metric ton basis by (1 – the material's moisture content) and by converting from metric tons to short tons of material.

2.2.2 Component-Specific Decay Rates

The second factor in estimating material-specific landfill emissions is the rate at which a material decays under anaerobic conditions in the landfill. The decay rate is an important factor that influences the landfill collection efficiency described further in the next section. Although the final adjusted CH_4 yield shown in Exhibit 6 will eventually occur no matter what the decay rate, the rate at which the material decays influences how much of the CH_4 yield will eventually be captured for landfills with collection systems.

Recent studies by De la Cruz and Barlaz (2010) found that different materials degrade at different rates relative to bulk MSW rates of decay. For example, one short ton of a relatively inert wood material—such as lumber—will degrade slowly and produce a smaller amount of methane than food scraps, which readily decay over a much shorter timeframe. Materials will also degrade faster under wetter landfill conditions. Consequently, the rate at which CH_4 emissions are generated from decaying material in a landfill depends upon: (1) the type of material placed in the landfill, and (2) the moisture conditions of the landfill.

De la Cruz and Barlaz (2010) measured component-specific decay rates in laboratory experiments that were then scaled to field-level, component-specific decay rates based on mixed MSW field-scale decay rates published in EPA (1998) guidance.

To scale the laboratory-scale, component-specific decay rate measurements to field-scale values, De la Cruz and Barlaz (2010) assumed that the weighted average decay rate for a waste mixture of the same composition as MSW would be equal to the bulk MSW decay rate. They also related a lab-scale decay rate for mixed MSW to the field-scale decay rate using a scaling factor. Using these two relationships, the authors were able to estimate field-scale decay rates for different materials based on the laboratory data. The following equations were used to estimate the component-specific decay rates:

Equation 1

$$f \times \sum_{i=1}^{n} k_{lab,i} \times (wt.fraction)_i = decay\ rate$$

Equation 2

$$k_{field,i} = f \times k_{lab,i}$$

where,

f = a correction factor to force the left side of the equation to equal the overall MSW decay rate

$k_{lab,i}$ = the component-specific decay rate calculated from lab experiments

$k_{field,i}$ = the component-specific decay rate determined for the field

i = the i^{th} waste component

Based on the results from De la Cruz and Barlaz (2010), the Excel version of WARM allows users to select different component-specific decay rates based on different assumed moisture contents of the landfill to estimate the rate at which CH_4 is emitted for each material type (or "component"). The four MSW decay rates used are:

1. k = 0.02/year ("Dry"), corresponding to landfills receiving fewer than 25 inches of annual precipitation: a default value from EPA (1998)
2. k = 0.04/year ("Average"), corresponding to landfills receiving more than 25 inches of annual precipitation: a default value from EPA (1998)
3. k = 0.08/year ("Wet"), corresponding to landfills that are wetter than normal due to extreme precipitation or some leachate recirculation: based on expert judgment

4. k = 0.12/year ("Bioreactor"), corresponding to landfills operating as bioreactors: based on expert judgment.

The final waste component-specific decay rates as a function of landfill moisture conditions are provided in Exhibit 7.

Exhibit 7: Component-Specific Decay Rates (yr^{-1}) by Landfill Moisture Scenario

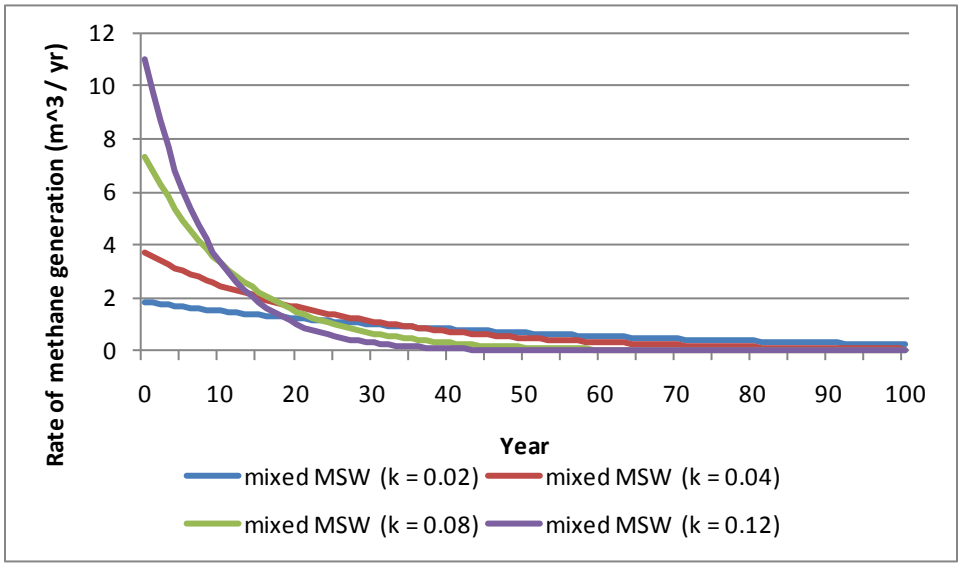
Material	Landfill Moisture Conditions			
	Dry	Average	Wet	Bioreactor
Corrugated Containers	0.01	0.02	0.04	0.06
Magazines/Third-Class Mail	0.06	0.12	0.24	0.37
Newspaper	0.02	0.03	0.07	0.10
Office Paper	0.02	0.03	0.06	0.09
Phone Books	0.02	0.03	0.07	0.10
Textbooks	0.02	0.03	0.06	0.09
Dimensional Lumber	0.01	0.02	0.03	0.05
Medium-Density Fiberboard	0.01	0.02	0.03	0.05
Food Scraps	0.07	0.14	0.29	0.43
Yard Trimmings	0.10	0.20	0.39	0.59
Grass	0.15	0.30	0.60	0.90
Leaves	0.09	0.17	0.34	0.51
Branches	0.01	0.02	0.03	0.05
Mixed MSW	0.02	0.04	0.08	0.12
Drywall[1]	–	–	–	–
Wood Flooring[1]	–	–	–	–

– = Zero Emissions.

[1]Decay rates were not estimated since WARM assumes that the construction and demolition landfills where these materials are disposed of do not collect landfill gas.

The profile of methane emissions as materials decay in landfills over time is commonly approximated using a first-order decay methodology summarized in De la Cruz and Barlaz (2010). The CH_4 generation potential of landfilled waste decreases gradually throughout time and can be estimated using first order decomposition mathematics. The profile of methane emissions from landfills over time for mixed MSW is shown in Exhibit 8 as a graphic representation of the methane emissions approximated using a first-order decay equation. As Exhibit 8 shows, materials will degrade faster under wetter conditions in landfills (i.e., landfills whose conditions imply higher decay rates for materials).

Exhibit 8. Rate of Methane Generation for Mixed MSW as a Function of Decay Rate



Although in each landfill moisture scenario, the total final CH_4 yield for solid waste components (Exhibit 6) will eventually be emitted over time, the rate at which methane is emitted greatly depends on the decay rate. Finally, since different materials have very different methane emission profiles in landfills, the effectiveness and timing of the installation of landfill gas collection systems can greatly influence methane emissions, as discussed in the next section.

2.2.3 Landfill Gas Collection

Finally, WARM estimates the amount of methane that is collected by landfill gas collection equipment. In practice, the landfill gas collection system efficiency does not remain constant over the duration of gas production. Rather, the gas collection system at any particular landfill is typically expanded over time. Usually, only a small percentage (or none) of the gas produced soon after waste burial is collected, while almost all of the gas produced is collected once a final cover is installed. Consequently, EPA uses temporally-weighted average gas collection efficiencies to provide a better estimate of gas collection system efficiency (Barlaz et al., 2009).

The temporally-averaged gas collection efficiencies that WARM uses are evaluated from the perspective of a short ton of a specific material placed in the landfill at year zero. The efficiencies are calculated based on one of four moisture conditions (dry, average, wet, and bioreactor conditions, described in section 2.2.2) and one of three landfill gas collection practices over a 100-year time period, which is approximately the amount of time required for 95 percent of the potential landfill gas to be produced under the "Dry" (k = 0.02/yr) landfill scenario. The final average efficiency is equal to the total CH_4 collected over 100 years divided by the total CH_4 produced over 100 years.

The combination of three different landfill gas collection scenarios and four different landfill moisture conditions means there are 12 possible landfill gas collection efficiencies possible for each material in WARM. The landfill collection efficiency scenarios are described below and the assumptions for each are shown in Exhibit 9:

1. Typical collection – phased-in collection with an improved cover
2. Worst-case collection – the minimum collection requirements under EPA's New Source Performance Standards
3. Aggressive collection – equivalent to typical bioreactor operations.

Exhibit 9: WARM Gas Collection Scenario Assumptions and Efficiencies Compared to EPA AP-42 (1998)

Scenario	Gas Collection Scenario Description	Gas Collection Scenario	Landfill Gas Collection Efficiency (%)			
			MSW Decay Rate (yr^{-1})			
			0.02	0.04	0.08	0.12
AP-42	EPA default gas collection assumption (EPA 1998 AP-42) (not modeled in WARM)	All years: 75%	75.0	75.0	75.0	75.0
1	Phased in collection with improved cover ("Typical collection")	Years 1–2: 0% Year 3: 50% Years 4–7: 75% Years 8–100: 95%	89.2	85.1	77.0	NA
2	"Worst-case collection" under EPA New Source Performance Standards (NSPS)	Years 0-5: 0% Years 6–7: 75% Years 8–100: 95%	84.8	77.9	64.5	NA
3	"Aggressive gas collection," typical bioreactor operation	Year 1: 25% Years 2–3: 50% Years 4–7: 75% Years 8–100: 95%	NA	87.5	81.6	76.6

NA = Not applicable.

The landfill gas collection efficiencies by material type for each of the three landfill collection efficiency scenarios and each of the four moisture conditions are provided Exhibit 10.

For landfill gas that is not collected, EPA takes into account the percentage of landfill CH_4 that is oxidized near the surface of the landfill. Based on estimates in the literature, EPA assumes that 10 percent of the landfill CH_4 generated is either chemically oxidized or converted by bacteria to CO_2,[4] and the remaining 90 percent is emitted as CH_4.

[4] An oxidation rate of 10 percent is cited by Liptay et al. (1998) and Czepiel et al. (1996). The rate of 10 percent is also recommended by the Intergovernmental Panel on Climate Change.

Exhibit 10: Waste Component-Specific Collection Efficiencies by Landfill Moisture Condition

Material/ Product	Typical Landfill Scenario				Worst-Case Landfill Scenario				Aggressive Collection Landfill Scenario			
	Dry	Avg.	Wet	Bio-reactor	Dry	Avg.	Wet	Bio-reactor	Dry	Avg.	Wet	Bio-reactor
Corrugated Containers	91%	89%	85%	81%	88%	85%	78%	71%	92%	91%	88%	85%
Magazines/ Third-Class Mail	90%	87%	80%	74%	86%	81%	70%	60%	91%	89%	84%	80%
Newspaper	90%	87%	80%	74%	86%	80%	69%	59%	91%	89%	84%	79%
Office Paper	90%	87%	81%	76%	86%	82%	71%	62%	91%	89%	85%	81%
Phone Books	90%	87%	80%	74%	86%	80%	69%	59%	91%	89%	84%	79%
Textbooks	90%	87%	81%	76%	86%	82%	71%	62%	91%	89%	85%	81%
Dimensional Lumber	91%	90%	87%	84%	89%	86%	81%	76%	92%	91%	89%	87%
Medium-Density Fiberboard	91%	90%	87%	84%	89%	86%	81%	76%	92%	91%	89%	87%
Food Scraps	79%	66%	49%	37%	67%	48%	24%	12%	83%	74%	63%	56%
Yard Trimmings	74%	60%	41%	29%	60%	38%	16%	7%	79%	70%	58%	52%
Grass	65%	48%	28%	17%	46%	23%	6%	2%	73%	62%	51%	45%
Leaves	76%	62%	44%	32%	63%	42%	19%	9%	81%	71%	60%	53%
Branches	91%	90%	87%	84%	89%	86%	81%	76%	92%	91%	89%	87%
Mixed MSW	89%	85%	77%	70%	85%	78%	65%	53%	91%	88%	82%	77%
Gypsum[1]	–	–	–	–	–	–	–	–	–	–	–	–
Wood Flooring[1]	–	–	–	–	–	–	–	–	–	–	–	–

– = Zero Emissions.

[1]WARM assumes that construction and demolition landfills do not collect landfill gas.

2.3 EMISSIONS FROM TRANSPORTATION TO LANDFILLS AND LANDFILL OPERATION

In addition to CH_4 emissions from waste decomposition in landfills, WARM includes transportation CO_2 emissions from collecting MSW and running landfill operational equipment in each material type's landfill emission factor. The amount of diesel fuel required to collect a short ton of waste and operate the necessary equipment to manage the landfill was taken from FAL (1994). Exhibit 11 provides the transportation emission factor calculation.

Exhibit 11: Transportation CO_2 Emissions Assumptions and Calculation

Equipment	Diesel Fuel (gallons/ 10^3 lbs of MSW landfilled)	Total Energy (Btu/10^3 lb of MSW landfilled)	Total Energy (Btu/Short Ton of MSW landfilled)	MTCE (per million Btus)	Total ($MTCO_2E$/Short Ton)
Collection Vehicles	0.90	148,300	296,600	–	–
Landfill Equipment	0.70	115,400	230,800	–	–
Total	**1.6**	**263,700**	**527,400**	**0.02**	**0.04**

– = Zero Emissions.

2.4 ESTIMATING LANDFILL CARBON STORAGE

The other anthropogenic fate of carbon in landfills is storage. As described in section 2.1, a portion of the carbon in biodegradable materials (i.e., food scraps, yard trimmings, paper and wood)

that is not completely decomposed by anaerobic bacteria remains stored in the landfill. This carbon storage would not normally occur under natural conditions, so it is counted as an anthropogenic sink (IPCC, 2006; Bogner et al., 2007).

The discussion in section 2.2 on initial carbon contents and CH_4 generation includes the measured carbon stored from the Barlaz (1998) experiments. For the most part, the amount of stored carbon measured as the output during these experiments is considered the final ratio of carbon stored to total initial dry weight of each material type. For coated paper, which is a proxy for magazines and third-class mail, the amount of carbon stored is reduced because carbon outputs were *greater than* initial carbon.

To estimate the final carbon storage factor, the proportion of initial carbon stored found in Exhibit 5 is multiplied by the initial carbon contents in Exhibit 3 to obtain the ratio of carbon storage to dry weight for each material type found in Exhibit 12. These estimates are then converted from dry weight to wet weight and from grams to metric tons of CO_2 per wet short ton of material. The last column of Exhibit 12 provides the final carbon storage factors for the biodegradable solid waste components modeled in WARM.

Exhibit 12: Carbon Storage for Solid Waste Components

Material/Product	Ratio of Carbon Storage to Dry Weight (gram C/dry gram)	Ratio of Dry Weight to Wet Weight	Ratio of Carbon Storage to Wet Weight (gram C/wet gram)	Amount of Carbon Stored ($MTCO_2E$ per Wet Short Ton)
Corrugated Containers	0.26	0.95	0.25	0.82
Magazines/Third-Class Mail	0.26	0.95	0.25	0.82
Newspaper	0.42	0.95	0.40	1.33
Office Paper	0.05	0.95	0.05	0.16
Phone Books	0.42	0.95	0.40	1.33
Textbooks	0.05	0.95	0.05	0.16
Dimensional Lumber	0.38	0.90	0.34	1.14
Medium-Density Fiberboard	0.38	0.90	0.34	1.14
Food Scraps	0.08	0.30	0.02	0.08
Yard Trimmings	0.31	0.55	0.19	0.63
Grass	0.24	0.30	0.07	0.24
Leaves	0.39	0.70	0.27	0.90
Branches	0.38	0.90	0.34	1.14
Mixed MSW	0.08	0.84	0.07	0.22
Drywall	0.03	0.94	0.03	0.09
Wood Flooring	0.38	0.75	0.29	0.95

2.5 ELECTRIC UTILITY GHG EMISSIONS AVOIDED

The CH_4 component of landfill gas that is collected from landfills can be combusted to produce heat and electricity, and recovery of heat and electricity from landfill gas offsets the combustion of other fossil fuel inputs. WARM models the recovery of landfill gas for electricity generation and assumes that this electricity offsets non-baseload electricity generation in the power sector.

WARM applies non-baseload electricity emission rates to calculate the emissions offset from landfill gas energy recovery because the model assumes that incremental increases in landfill energy recovery will affect non-baseload power plants (i.e., power plants that are “demand-following” and

adjust to marginal changes in the supply and demand of electricity). EPA calculates non-baseload emission rates as the average emissions rate from power plants that combust fuel and have capacity factors less than 0.8 (EPA, 2010a).

EPA estimates the avoided GHG emissions per $MTCO_2E$ of CH_4 combusted using several physical constants and data from EPA's Landfill Methane Outreach Program and eGRID (EPA, 2010b; EPA, 2010a). The mix of fuels used to produce electricity varies regionally in the United States; consequently, EPA applies a different CO_2-intensity for electricity generation depending upon where the electricity is offset. The Excel version of WARM includes CO_2-intensity emission factors for non-baseload electricity generated in nine different U.S. regions as well as a U.S.-average CO_2-intensity (EPA, 2010a). The formula used to calculate the quantity of electricity generation emissions avoided per $MTCO_2E$ of CH_4 combusted is as follows:

$$\frac{BTU_{CH4}}{H_{LFGTE}} \times a \times E_{Grid} = R$$

Where:

Btu_{CH4} = Energy content of CH_4 per $MTCO_2E$ CH_4 combusted; assumed to be 1,012 Btu per cubic foot of CH_4 (EPA, 2010b), converted into Btu per $MTCO_2E$ CH_4 assuming 20 grams per cubic foot of CH_4 at standard temperature and pressure and a global warming potential of CH_4 of 21

H_{LFGTE} = Heat rate of landfill gas to energy conversion; assumed to be 11,700 Btu per kWh generated (EPA, 2010b)

a = Net capacity factor of electricity generation; assumed to be 85 percent (EPA, 2010b)

E_{grid} = Non-baseload CO_2-equivalent GHG emissions intensity of electricity produced at the regional or national electricity grid; values assumed for each region and U.S. average are shown in Exhibit 14

R = Ratio of GHG emissions avoided from electricity generation per $MTCO_2E$ of CH_4 combusted for landfill gas to energy recovery

Exhibit 13 shows variables in the GHG emissions offset for the national average fuel mix. The final ratio is the product of columns (a) through (h). Exhibit 14 shows the amount of carbon avoided per kilowatt-hour of generated electricity and the final ratio of $MTCO_2E$ avoided of utility carbon per $MTCO_2E$ of CH_4 combusted (column (g) and resulting column (i)).

Exhibit 13: Calculation to Estimate Utility GHGs Avoided through Combustion of Landfill CH_4 for Electricity Based on National Average Electricity Grid Mix

(a) Metric Tons CH_4/$MTCO_2E$ CH_4 Combusted	(b) Grams CH_4/Metric Ton CH_4	(c) Cubic Ft. CH_4/ Gram CH_4	(d) Btu/Cubic Ft. CH_4	(e) kWh Electricity Generated / Btu	(f) Electricity Generation Efficiency	(g) Kg Utility CO_2 Avoided/ kWh Generated Electricity	(h) Metric Tons Avoided Utility CO_2/Kg Utility CO_2	(i) Ratio of $MTCO_2E$ Avoided Utility CO_2 per $MTCO_2E$ CH_4 Combusted
0.05	1,000,000	0.05	1012	0.00	0.85	0.74	0.00	0.13

Exhibit 14: Ratio of $MTCO_2E$ Avoided Utility Carbon per $MTCO_2E$ CH_4 Combusted by Region

Region	Kg Utility CO_2 Avoided/kWh Generated Electricity	Ratio of $MTCO_2E$ Avoided Utility C per $MTCO_2E$ CH_4
Pacific	0.54	0.10

Mountain	0.96	0.17
West-North Central	0.89	0.16
West-South Central	0.75	0.13
East-North Central	0.74	0.13
East-South Central	0.60	0.10
New England	0.58	0.10
Mid Atlantic	0.99	0.17
South Atlantic	0.78	0.14
National Average	0.74	0.13

If regional avoided utility emission factors are not employed, WARM calculates U.S.-average avoided utility emission factors based on the percent of CH_4 generated at landfills in the nation with landfill gas recovery and electricity production found in Exhibit 1, and assuming U.S.-average, non-baseload electricity GHG emission intensity. Exhibit 15 shows this calculation for each material type for the national average fuel mix.

Exhibit 15: Overall Avoided Utility CO_2 Emissions per Short Ton of Waste Material (National Average Grid Mix)

(a)	(b)	Methane from Landfills With LFG Recovery and Electricity Generation					(h)
		(c)	(d)	(e)	(f)	(g)	
Material	CH_4 Generation ($MTCO_2E$/ Wet Short Ton) (Exhibit 6)	% of CH_4 Not Recovered (100% Minus LFG Collection System Efficiency (Exhibit 10)	Utility GHG Emissions Avoided per $MTCO_2E$ CH_4 Combusted ($MTCO_2E$) (Exhibit 14)	% of CH_4 Recovered for Electricity Generation Not Utilized Due to LFG System "Down Time"	Utility GHG Emissions Avoided ($MTCO_2E$/Wet Short Ton) (f = b × (1-c) × d × (1-e))	CH_4 From Landfills With LFG Recovery and Electricity Generation (Exhibit 1)	Net Avoided CO_2 Emissions from Energy Recovery ($MTCO_2E$/ Wet Short Ton) (h = f × g)
Corrugated Containers	2.52	11%	-0.13	15%	-0.25	34%	-0.08
Magazines/ Third-Class Mail	1.02	13%	-0.13	15%	-0.10	34%	-0.03
Newspaper	0.90	13%	-0.13	15%	-0.09	34%	-0.03
Office Paper	4.26	13%	-0.13	15%	-0.41	34%	-0.14
Phone Books	0.90	13%	-0.13	15%	-0.09	34%	-0.03
Textbooks	4.26	13%	-0.13	15%	-0.41	34%	-0.14
Dimensional Lumber	1.30	10%	-0.13	15%	-0.13	34%	-0.04
Medium-Density Fiberboard	1.30	10%	-0.13	15%	-0.13	34%	-0.04
Food Scraps	1.63	34%	-0.13	15%	-0.12	34%	-0.04
Yard Trimmings	0.88	40%	-0.13	15%	-0.06	34%	-0.02
Grass	0.80	52%	-0.13	15%	-0.04	34%	-0.01
Leaves	0.62	38%	-0.13	15%	-0.04	34%	-0.01
Branches	1.30	10%	-0.13	15%	-0.13	34%	-0.04
Mixed MSW	3.64	15%	-0.13	15%	-0.34	34%	-0.12
Drywall[1]	0.20	–	-0.13	15%	-0.02	–	–
Wood Flooring[1]	1.09	–	-0.13	15%	-0.12	–	–

– = Zero Emissions.

[1] WARM assumes that construction and demolition landfills do not collect landfill gas.

2.6 NET GHG EMISSIONS FROM LANDFILLING

CH_4 emissions, transportation CO_2 emissions, carbon storage and avoided utility GHG emissions are then summed to estimate the net GHG emissions from landfilling each material type. Exhibit 16 shows the net emission factors for landfilling each material based on typical landfill gas collection practices, average landfill moisture conditions (i.e., for landfills receiving greater than 25 inches of precipitation annually), and U.S.-average non-baseload electricity grid mix.

Exhibit 16: Net GHG Emissions from Landfilling ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided GHG Emissions from Energy Recovery (Exhibit 15)	Landfill Carbon Storage (Exhibit 12)	Net Emissions (Post-Consumer)
Aluminum Cans	–	0.04	0.00	0.00	0.00	0.04
Aluminum Ingot	–	0.04	0.00	0.00	0.00	0.04
Steel Cans	–	0.04	0.00	0.00	0.00	0.04
Copper Wire	–	0.04	0.00	0.00	0.00	0.04
Glass	–	0.04	0.00	0.00	0.00	0.04
HDPE	–	0.04	0.00	0.00	0.00	0.04
LDPE	–	0.04	0.00	0.00	0.00	0.04
PET	–	0.04	0.00	0.00	0.00	0.04
LLDPE	–	0.04	0.00	0.00	0.00	0.04
PP	–	0.04	0.00	0.00	0.00	0.04
PS	–	0.04	0.00	0.00	0.00	0.04
PVC	–	0.04	0.00	0.00	0.00	0.04
PLA	–	0.04	0.00	0.00	-1.66	-1.62
Corrugated Containers	–	0.04	0.82	-0.08	-0.82	-0.05
Magazines/Third-Class Mail	–	0.04	0.35	-0.03	-0.82	-0.47
Newspaper	–	0.04	0.32	-0.03	-1.33	-1.01
Office Paper	–	0.04	1.43	-0.14	-0.16	1.17
Phone Books	–	0.04	0.32	-0.03	-1.33	-1.01
Textbooks	–	0.04	1.43	-0.14	-0.16	1.17
Dimensional Lumber	–	0.04	0.42	-0.04	-1.14	-0.73
Medium-Density Fiberboard	–	0.04	0.42	-0.04	-1.14	-0.73
Food Scraps	–	0.04	0.77	-0.04	-0.08	0.69
Yard Trimmings	–	0.04	0.45	-0.02	-0.63	-0.16
Grass	–	0.04	0.47	-0.01	-0.24	0.26
Leaves	–	0.04	0.31	-0.01	-0.90	-0.56
Branches	–	0.04	0.42	-0.04	-1.14	-0.73
Mixed Paper						
Mixed Paper (general)	–	0.04	0.78	-0.08	-0.81	-0.07
Mixed Paper (primarily residential)	–	0.04	0.74	-0.07	-0.84	-0.14
Mixed Paper (primarily from offices)	–	0.04	0.77	-0.08	-0.67	0.06
Mixed Metals	–	0.04	0.00	0.00	0.00	0.04
Mixed Plastics	–	0.04	0.00	0.00	0.00	0.04
Mixed Recyclables	–	0.04	0.63	-0.06	-0.73	-0.13

Mixed Organics	–	0.04	0.62	-0.03	-0.35	0.28
Mixed MSW	–	0.04	1.28	-0.12	-0.22	0.98
Carpet	–	0.04	0.00	0.00	0.00	0.04
Personal Computers	–	0.04	0.00	0.00	0.00	0.04
Clay Bricks	–	0.04	0.00	0.00	0.00	0.04
Concrete	–	0.04	0.00	0.00	0.00	0.04
Fly Ash	–	0.04	0.00	0.00	0.00	0.04
Tires	–	0.04	0.00	0.00	0.00	0.04
Asphalt Concrete	–	0.04	0.00	0.00	0.00	0.04
Asphalt Shingles	–	0.04	0.00	0.00	0.00	0.04
Drywall	–	0.04	0.18	0.00	-0.09	0.13
Fiberglass Insulation	–	0.04	0.00	0.00	0.00	0.04
Vinyl Flooring[1]	–	0.04	0.00	0.00	0.00	0.04
Wood Flooring[1]	–	0.04	0.98	0.00	-0.95	0.07

– = Zero Emissions.
[1] WARM assumes that construction and demolition landfills do not collect landfill gas

In WARM, emissions from landfills are dependent on the user selection of one of four different landfill scenarios (i.e., “Landfills: National Average,” “Landfills Without LFG Recovery,” “Landfills With LFG Recovery and Flaring,” and “Landfills With LFG Recovery and Electric Generation”) as described in section 1. The net landfilling emission factors for landfilling each material based on the default options in WARM (i.e., typical landfill gas collection practices, average landfill moisture conditions and U.S.-average non-baseload electricity grid mix) are shown in Exhibit 17.

Exhibit 17: Landfilling Net Emission Factors in WARM Using Default Options ($MTCO_2E$/Ton)

Material	Landfills: National Average (Exhibit 16)	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Aluminum Cans	0.04	0.04	0.04	0.04
Aluminum Ingot	0.04	0.04	0.04	0.04
Steel Cans	0.04	0.04	0.04	0.04
Copper Wire	0.04	0.04	0.04	0.04
Glass	0.04	0.04	0.04	0.04
HDPE	0.04	0.04	0.04	0.04
LDPE	0.04	0.04	0.04	0.04
PET	0.04	0.04	0.04	0.04
LLDPE	0.04	0.04	0.04	0.04
PP	0.04	0.04	0.04	0.04
PS	0.04	0.04	0.04	0.04
PVC	0.04	0.04	0.04	0.04
PLA	-1.62	-1.62	-1.62	-1.62
Corrugated Containers	-0.05	1.49	-0.54	-0.79
Magazines/Third-Class Mail	-0.47	0.14	-0.66	-0.76
Newspaper	-1.01	-0.48	-1.18	-1.27
Office Paper	1.17	3.71	0.36	-0.05
Phone Books	-1.01	-0.48	-1.18	-1.27
Textbooks	1.17	3.71	0.36	-0.05
Dimensional Lumber	-0.73	0.07	-0.98	-1.11
Medium-Density Fiberboard	-0.73	0.07	-0.98	-1.11
Food Scraps	0.69	1.43	0.46	0.34
Yard Trimmings	-0.16	0.20	-0.27	-0.33
Grass	0.26	0.51	0.17	0.13
Leaves	-0.56	-0.30	-0.65	-0.69
Branches	-0.73	0.07	-0.98	-1.11
Mixed Paper (general)	-0.07	1.35	-0.49	-0.71
Mixed Paper (primarily residential)	-0.14	1.21	-0.53	-0.75
Mixed Paper (primarily from offices)	0.06	1.43	-0.23	-0.43
Mixed Metals	0.04	0.04	0.04	0.04
Mixed Plastics	0.04	0.04	0.04	0.04
Mixed Recyclables	-0.13	1.02	-0.45	-0.63
Mixed Organics	0.28	0.83	0.11	0.02
Mixed MSW	0.98	3.10	0.31	-0.03
Carpet	0.04	0.04	0.04	0.04
Personal Computers	0.04	0.04	0.04	0.04
Clay Bricks	0.04	0.04	0.04	0.04
Concrete	0.04	0.04	0.04	0.04
Fly Ash	0.04	0.04	0.04	0.04
Tires	0.04	0.04	0.04	0.04
Asphalt Concrete	0.04	0.04	0.04	0.04
Asphalt Shingles	0.04	0.04	0.04	0.04
Drywall	0.13	0.13	0.13	0.13
Fiberglass Insulation	0.04	0.04	0.04	0.04
Vinyl Flooring	0.04	0.04	0.04	0.04
Wood Flooring	0.07	0.07	0.07	0.07

3. LIMITATIONS

The landfilling analysis has several limitations associated with it; these are discussed in the following paragraphs.

- Perhaps the most important caveat to the analysis of GHG emissions and storage associated with landfilling is that most of the results are based on a single set of laboratory experiments conducted by Dr. Morton Barlaz (1998). Although researchers other than Dr. Barlaz have conducted laboratory studies that track the degradation of mixed MSW, his experiments were the only ones EPA identified at the time this analysis was conducted that rigorously tested materials on an individual basis. Dr. Barlaz is recognized as an expert on the degradation of different fractions of MSW under anaerobic conditions, and his findings with respect to the CH_4 potential of mixed MSW are within the range used by landfill gas developers. Nevertheless, given the sensitivity of the landfill results to estimated CH_4 generation and carbon storage, EPA recognizes that more research is needed in this area.
- The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high global warming potential of CH_4, small changes in the LFG recovery rate (for the national average landfill) could have a large effect on the net GHG impacts of landfilling each material and the ranking of landfilling relative to other MSW management options.
- Landfills with LFG recovery may be permitted, under EPA regulations, to remove the LFG recovery equipment when three conditions are met: (1) the landfill is permanently closed, (2) LFG has been collected continuously for at least 15 years, and (3) the landfill emits less than 50 metric tons of non-CH_4 organic compounds per year (61 FR 49, 1996). Although the removal of LFG recovery equipment will permit CH_4 from closed landfills to escape into the atmosphere, the amounts of CH_4 emitted should be relatively small, because of the length of time required for LFG collection before LFG recovery equipment is removed.
- The distribution of waste in place is not a perfect proxy for the distribution of ongoing waste generation destined for landfill.
- Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH_4 generation and collection. As more landfills install effective covers and implement controls to keep water and other liquids out, conditions will be less favorable for degradation of biodegradable wastes. Over the long term, these improvements may result in a decrease in CH_4 generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH_4 yields from his laboratory experiments are likely to be higher than CH_4 yields in a landfill, because the laboratory experiments were designed to generate the maximum amount of CH_4 possible. If the CH_4 yields from the laboratory experiments were higher than yields in a landfill, the net GHG emissions from landfilling biodegradable materials would be lower than estimated here.
- EPA assumed that once wastes are disposed in a landfill, they are never removed. In other words, it was assumed that landfills are never "mined." A number of communities have mined their landfills—removing and combusting the waste—in order to create more space for continued disposal of waste in the landfill. To the extent that landfills are mined in the

future, it is incorrect to assume that carbon stored in a landfill will remain stored. For example, if landfilled wastes are later combusted, the carbon that was stored in the landfill will be oxidized to CO_2 in the combustor.

- The estimate of avoided utility GHG emissions per unit of CH_4 combusted assumes that all landfill gas-to-energy projects produce electricity. In reality, some projects are "direct gas" projects, in which CH_4 is piped directly to the end user for use as fuel. In these cases, the CH_4 typically replaces natural gas as a fuel source. Because natural gas use is less GHG-intensive than average electricity production, direct gas projects will tend to offset fewer GHG emissions than electricity projects will—a fact not reflected in the analysis.
- For landfilling of yard trimmings (and other organic materials), EPA assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a non-landfill environment. In other words, it was assumed that in a baseline where yard trimmings are returned to the soil (i.e., in a non-landfill environment), all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO_2, and there is no long-term carbon storage. To the extent that long-term carbon storage occurs in the baseline, the estimates of carbon storage reported here are overstated, and the net postconsumer GHG emissions are understated.
- The key assumptions that have not already been discussed as limitations are the assumptions used in developing "corrected" CH_4 yields for biodegradable materials in MSW. Because of the high GWP of CH_4, a small difference between estimated and actual CH_4 generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

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